STABILIZATION OF BEAM INSTABILITY DUE TO SPACE-CHARGE EFFECTS AT J-PARC

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Abstract

Kicker magnets are ones of dominant sources of impedances in the 3GeV Rapid Cycling Synchrotron (RCS) at Japan Proton Accelerator Research Complex (J-PARC). They may be limiting factors in achieving high intensity beams. Recently, the 300kW beam was accomplished at 3GeV RCS, while no instability was observed. In this paper, the space-charge effects are studied as beam stabilization effects.

INTRODUCTION

J-PARC [1] consists of the 181 MeV LINAC, the 3GeV RCS and the Main Ring (MR). The RCS operates at repetition rates of 25 Hz and provides 3GeV proton beams to the Materials and Life Science Experimental Facility and MR. The final goal of RCS beam power is 1MW after the upgrade of LINAC energy to 400 MeV. In this paper, we focus on the issues of the RCS and discuss about the stabilization effects of the space-charge force against the beam instabilities.

TRANSVERSE INSTABILITIES WITHOUT SPACE-CHARGE EFFECTS

The impedance budget of the transverse impedance shows that the kicker impedance is the dominant source in the RCS. Actually, the measurement results show that there are sharp peaks in the RCS kicker impedances (see Fig.1.)[2, 3, 4, 5]. They are about 10 times larger than those of SNS kickers [6]. The sharp peaks are due to cable resonances of beam-induced currents in the kicker magnet.

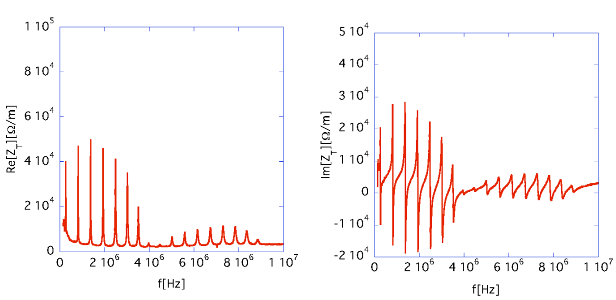

Figure 1: The measurement results of a kicker impedance of the RCS. The left and the right figures show the real and the imaginary parts, respectively. The total number of the kicker magnets n_k is eight in the RCS.

There is a conventional formula for estimate of the growth rate of beam positions, using impedances Z_T as input data [7, 8]:

$$\tau_m^{-1} = -\frac{I_c c n_k}{(1+m)4\pi Q_T E/c} \sum_{p=-\infty}^{\infty} Z_T(\omega_p) F_m(\omega_p - \omega_\xi), \quad (1)$$

$$F_m = \frac{h_m(\omega)}{B_f \sum_{q=-\infty}^{\infty} h_m(\omega_q - \omega_\xi)}, \quad (2)$$

$$h_m(\omega) = \frac{\tau_L^2 (m+1)^2 [1 + (-1)^m \cos(\omega \tau_L)]}{2\pi^4 [(\omega\tau_L/\pi)^2 - (m+1)^2]^2}, \quad (3)$$

$$\omega_\xi = 2\pi f_0 \xi Q_T/\eta, \tau_L = \frac{B_f}{h f_0}, \quad (4)$$

$$\omega_p = 2\pi f_0 (ph + \mu + Q_T + m\nu_s), \quad (5)$$

where E is the beam energy, ξ is the chromaticity, μ is the coupled bunch mode number $\mu = 0 ... h-1$, h is the harmonic number, m is the head-tail mode number. The main parameters in the RCS are summarized in Table 1.

Table 1: Parameter list of RCS(C=348.333,h=2, Repetition rate=25Hz)

T(kinetic energy, GeV)	0.181	3
f_0 (revolution freq., MHz)	0.47	0.84
η(slippage factor)	-0.69	-0.047
$Q_x/Q_y(=Q_T)$(tune)	6.68/6.27	
B_f(bunching factor)	0.374	0.185
N_b(proton/bunch)/10^{13}	2.49	2.49
I_c(average current, A)	3.74	6.7
I_p(peak current, A)	10	36
$\Delta p/p(\%)$	0.85	0.38
τ_z(half bunch length, m)	55	20
ν_s(synchrotron tune)	0.0058	0.0005

Using the measured kicker impedance, the highest growth rate among different head-tail modes during the acceleration was calculated, assuming that the chromaticity is corrected to zero in the whole energy. The results are shown in Fig.2. We can see that the sharp impedances of kicker magnets produce intolerable growth rate. This may be a significant constraint to increase the beam intensity beyond a few 100kW.

Formula (2) is derived from the linear theory where no betatron tune spread, no space-charge effects nor Landau damping effects are considered. For more accurate estimates of horizontal instabilities, simulations need to be done.

One of simulation codes, SIMPSONS, that was originally developed by S. Machida[9], can deal with the space-

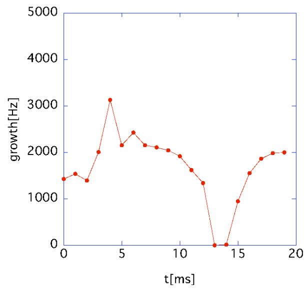

Figure 2: Horizontal instability due to the kicker magnets at 0.6 MW beam operation in the RCS. The chromaticity is corrected to zero in the entire energy. The growth rate will be halved at 300 kW beam operation.

charge effect in a single bunch. We modified SIMPSONS to include wake field effects and extended it for multi-bunch beam tracking [10].

Transverse instabilities without space-charge effect can be estimated more accurately, using the extended SIMPSONS code with kicker data. The results at 300 kW operation are shown in Fig.3. In this simulation, the chromaticity is corrected to zero in the entire energy. Without the space-charge effects, the kicker impedance increases the beam oscillation amplitude only in the horizontal direction. The growth rate during 0.2 ms to 1.5 ms is about 600 Hz, which is almost consistent with the theoretical prediction, shown in Fig.2. The oscillation amplitude is then damped after 1.5 ms. Landau damping starts to take effect after four synchrotron oscillation.

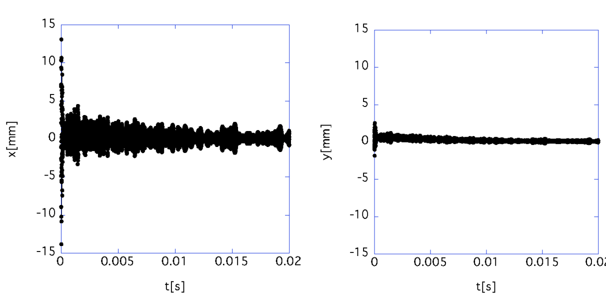

Figure 3: Transverse instability due to the kicker magnets without the space-charge effects at 300 kW operation in the RCS. The left and the right figures show the horizontal and the vertical beam positions, respectively. The chromaticity is corrected to zero in the entire energy.

In reality, the chromaticity is not fully corrected to zero at the present RCS set-up. It is corrected only at the injection energy using DC power supply. Figure 4 shows how the chromaticity changes from zero as the beam energy increases. The result for the case that chromaticity is corrected to zero only at the injection energy by DC power supply is shown in Fig.5. Comparing the results shown in Figs.3 and 5, we find that the partial correction of the chromaticity has a little effect on suppression of beam instabilities.

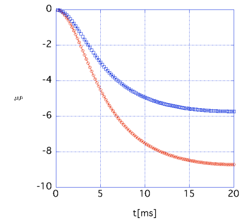

Figure 4: The behavior of chromaticity along time axis. The red and the blue lines show the horizontal and the vertical chromaticity, respectively.

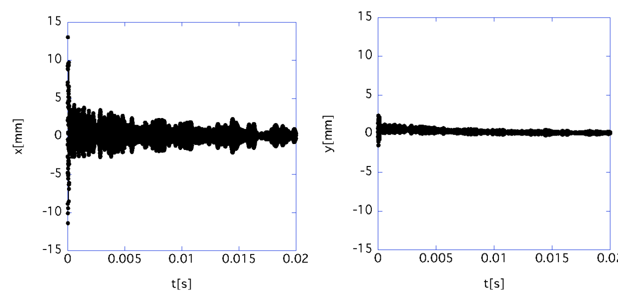

Figure 5: Transverse instability due to the kicker magnets without space-charge effects at 300 kW operation in the RCS. The left and the right figures show the horizontal and the vertical beam positions, respectively. The chromaticity is corrected to zero only at the injection energy.

MEASUREMENT AND SIMULATION RESULTS FOR A FEW HUNDRED KW BEAM

Since RCS is operated only up to 3 GeV, the space-charge effects are non-negligible for high intensity beams. Typically, the space-charge tune shift for 300 kW beam is around 0.15. In this section, we turn on the space-charge effects in our simulation code, and compare the simulation and the measurement results.

A tune spread prevents the coherent motion of a beam if it is sufficiently larger than the growth rate of the oscillation amplitude. Large space-charge effects are expected to contribute to the stabilization of the beam. According to Sacherer [7], the stability condition in the existence of betatron tune spread is given by

$$|\text{ Full-spread at half-height of } 2\pi Q_T f_0| > \text{growth rate.} \tag{6}$$

The stability condition at 300kW beam power is: a few hundred kHz$\sim>$ growth rate. This simple-minded analysis predicts that instabilities will be stabilized by the space-charge effects even at 1MW, which may be doubtful.

For more accurate estimations of beam instabilities, simulation should be done which includes both space-charge effects and the betatron tune spread effects due to the imperfect correction of chromaticity. Simulation results using SIMPSONS at 300 kW beam operation with the partial correction of the chromaticity are shown in Fig.6. Comparing the results in Fig.6 with those in Fig.5, we can see that space-charge effects significantly stabilize the beam. The oscillation amplitudes are of the same order of magnitude in both the horizontal and vertical directions, except during the injection period. This shows that the space-charge effects mix up the particle motion in the horizontal and the vertical directions in a bunch.

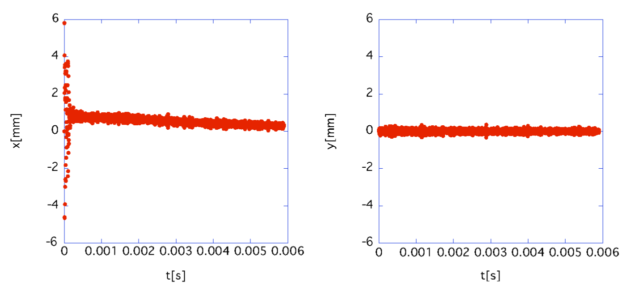

Figure 6: Simulation results at 300 kW beam operation with the space-charge effects. The left and the right figures show the horizontal and the vertical beam positions, respectively.

Recently, the beam power of 300 kW was accomplished at the RCS in a short period. The measurement results of transverse positions of the beam center during the 100 kW and 300 kW beam operation are shown in Figs.7 and 8, respectively. The left and the right figures in each figure show the horizontal and the vertical beam positions, respectively. The closed orbit distortion is extracted in these figures. While the oscillation amplitude is significantly

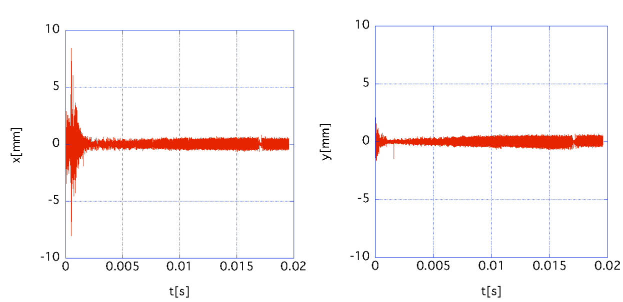

Figure 7: The measurement results for 100 kW beam operation. The left and the right figures show the horizontal and the vertical beam positions, respectively

increased in the horizontal direction during the injection periods, beams look stable in both cases in the acceleration periods. This trend is in agreement with the simulation result shown in Fig.6. It is remarkable that the oscillation amplitude at 300kW is smaller than that at 100kW, especially during the acceleration period. This behavior is consistent with the fact that the space-charge effects are stronger with

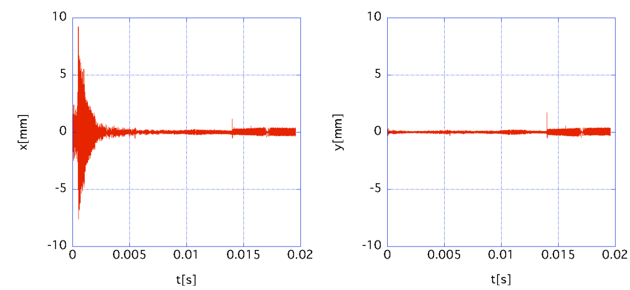

Figure 8: The measurement results for 300 kW beam operation. The left and the right figures show the horizontal and the vertical beam positions, respectively.

a 300 kW beam.

SUMMARY

The measurement and simulation results of the beam positions at 300 kW beam operation imply that the betatron tune spread due to the space-charge effects stabilizes the beam. Measurement results show that beam is more stabilized at 300 kW beam operation compared to at 100 kW, presumably due to the stronger space-charge effects.

ACKNOWLEDGEMENTS

The authors would like to thank the members of J-PARC project at JAEA/KEK.

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